Model of Fuel Economy with Applications to Driving Cycles and Traffic Management

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Fuel consumption by a vehicle is expressed in terms of a few vehicle characteristics and summary characteristics of any trip. This simple physical model can readily be adapted to any vehicle or combination of vehicles. The needed data for U.S. vehicles are in the public domain. Numerical results in the applications discussed are for an average U.S. car. One potential application is in modifying driving cycles to more accurately reflect actual driving behavior. The model shows that instead of a second-by-second velocity pattern being needed, fuel consumption depends on a small number of speed characteristics that summarize a trip: average speed, an average peak speed, braking time, stop time, and number of stops per unit distance. A second application concerns traffic management and fuel consumption. Average speed is the main determinant of fuel use. Attempted top speed of free-flow velocity is also an important determinant. Together, these driving characteristics enable a reasonable estimate of fuel consumption for planning purposes. For example, measures that increase traffic speed (up to about 50 mph) while decreasing maximum speed improve fuel economy. In these applications and others that are discussed, the coefficients are fundamental characteristics of the vehicles involved.

In two previous papers we developed a simple analytic approximation for fuel use by an automobile in terms of a small number of fundamental engine and vehicle characteristics and a few characteristics of driving over the course of a trip (*1,2*). We call this a simple physical model, distinguishing it from simulation models, which are also physical but much more detailed, and regression models, where the coefficients are estimated statistically rather than being directly measured physically. In this paper, we first explore some model capabilities, determining the effects on fuel use of changing the gear shift schedule, varying cruise speed, and driving to maximize fuel economy. We then analyze some common driving cycles to enable us to reexpress the fuel use model in terms of independent trip characteristics: average speed, target maximum speed, vehicle stop time, and, perhaps, number of stops. In this form, the model is a practical tool to help modify driving cycles so they reflect changes in driving behavior, estimate the effect of traffic management measures on fuel use, and analyze metropolitan area fuel use for planning purposes. Related work has also been done by Roumégoux (*3*).

The first paper in this series describes the simple (approximate) dependence of fuel use by engines based on systematic measurements made in the late 1970s (*4*):

$$\frac{P_f}{N} = a + \frac{1}{\eta}\frac{P_b}{N} \tag{1}$$

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where

P_f = rate of fuel energy use (kW),
P_b = rate of power output (kW), and
N = engine speed (revolutions per second).

The parameters are the engine's friction characteristic, a (fuel-energy rate at zero power output), which is approximately proportional to engine displacement, and a thermal efficiency characteristic, η, which is typically about 40 percent.

On the basis of this linear behavior, we showed in the second paper that fuel use in a trip can be approximately calculated in terms of certain additional vehicle characteristics and certain trip characteristics. The total trip time, T, has been divided into T_A, T_B, T_C, and T_D, where A incorporates periods of acceleration, B cruising and deceleration without brakes, C braking, and D vehicle stop. Thus $t_D = T_D/T$, for example.

The fuel use per unit distance, such as a kilometer or mile, is then

$$\varepsilon_{\text{fuel}} = [\alpha_{\text{f-pwr}}(1 - t_C - t_D)(v_{\text{gear}}/\bar{v}) + \alpha_{\text{f-idle}}(t_C + t_D)/\bar{v}] + (\alpha_{\text{tire}} + \alpha_{\text{air}}\lambda v_r^2 + \alpha_{\text{brake}}\beta v_p^2 n + \alpha_{\text{acc}}/\bar{v}) \tag{2}$$

The α's are vehicle-dependent coefficients defined in the appendix. (Units are also presented in the appendix.) The principal trip-dependent variables are as follows:

$\bar{v}$ = overall average speed, D/T;
v_r = average running speed, $D/(T - T_D)$;
v_p = average peak speed (root-mean-square of subcycle peak speeds);
n = number of stops per mile (or major slowdowns); and
t_C, t_D = fraction of time braking and stopped, respectively.

Note that $v_r(1 - t_D) = \bar{v}$.

Subsidiary trip variables that can be adequately estimated a priori are as follows:

v_{gear} = average vehicle speed in gear used in neighborhood of v_r times the gear ratio relative to that in top gear (discussed below);
λ = average of cubed running speed divided by the cube of the average, $\overline{v_r^3}/\bar{v}_r^3$, where, in this expression, only, v_r is the instantaneous running speed; and
β = fraction of vehicle kinetic energy absorbed by brakes (in regime C).

One finds that (*a*) using the Federal Test Procedure (FTP) gear-shifting schedule, $v_{gear} \approx 24.6$ m/sec (55 mph) for an M5 transmission; (*b*) $\lambda \approx 2.0$ for urban driving and $\lambda \approx 1.0$ for highway driving (1.90 and 1.09 in the EPA urban and highway cycles, respectively); and (*c*) $\beta \approx 0.9$ in urban driving and $\beta \approx 1.0$ in highway driving. If ε is in kJ fuel energy per kilometer (mile), then the fuel economy *FE*, in kilometers per liter (miles per gallon) is

$$FE = 31{,}850/\varepsilon \qquad (120{,}600/\varepsilon) \tag{3}$$

where the energy content (lower heating value) of the common test fuel is 31.85 MJ/L (120.6 MJ/gal).

The form of Equation 2 is closely related to that of Equation 1, with, in the first brackets, a generalized engine friction term proportional to a and to the total number of revolutions through which the engine turns during the trip, and, in the second brackets, a load term proportional to $1/\eta$. The latter is the incremental fuel use to provide for the four loads: tire loss, air drag loss, braking loss, and operation of vehicle accessories. Equation 2 is an approximation that enables determination of the fuel economy of a vehicle, from nonproprietary information, to an accuracy of about 5 percent (standard deviation). [In particular, the fuel economies of a large sample of 1991 cars with M5 transmissions have been fit using a simplified version of Equation 2, depending only on three variable vehicle characteristics, weight, engine displacement, and N/v (engine speed to vehicle speed in top gear), with a standard deviation of 4 percent (*2*).] In Equation 2, the engine friction term is about 60 to 70 percent of the total fuel use in typical urban driving and about 50 percent in highway driving. Thus the parameters in that term must be determined relatively accurately. The individual load terms are less important and so can be determined more roughly.

The allocation of fuel use to the different terms of Equation 2 is based on a certain set of energy sinks: generalized engine friction (pumping air into the cylinders and exhaust out, rubbing friction, and operating the engine accessories) and four loads on the engine (the three drive-wheel loads of tire, air, and brakes, including transmission losses, plus operating the vehicle accessories). This is a different allocation from that often made. For example, one could allocate the engine friction term during vehicle running proportionately to the four loads. Since the engine friction term is large, this dramatically alters the picture. An argument for our approach is that the generalized engine friction term depends on a basic attribute of driving, the number of revolutions of the engine in a trip. Thus the fuel use associated with the generalized engine friction is closely related to trip velocities but roughly independent of the loads.

Whereas the model and applications in this paper apply to a wide range of driving patterns, they do not apply to all driving. Engine speed, air drag, and braking have been approximated for convenience. Because of this, and because the driving characteristics v_r, n, v_p, t_C, and t_D may be strongly correlated, scenarios of the kinds of driving to be analyzed need to be developed.

We consider the following scenarios, and they provide the structure for the paper:

1. A driver follows a pattern of travel defined in detail. (However, if any of three kinds of driving—extremely high acceleration, extremely high speeds, or long coastdown—occur, engine speed, air drag, and braking energy, respectively, have to be estimated with special care.)

2a. An arbitrary trip is made about which only four or five characteristics are specified. (The same qualifications on unusual driving apply.)

2b. This scenario is the same as Item 2a except that the trip has qualities relating to slowing down and stopping shared by many existing driving cycles. At a minimum, only two trip characteristics need to be specified.

APPLICATIONS TO SPECIAL KINDS OF DRIVING

Effect of Gear Shifting on Fuel Economy

Aggressive drivers tend to accelerate and decelerate the vehicle more quickly than the average. Aggressive acceleration usually results in much higher engine speed, because with manual transmission the driver tends to shift later (at higher N), and with automatic transmission, the system delays shifting up. This results in increased use of fuel. (Aggressive deceleration causes excessive fuel use as well.) By the same token, in driving designed to reduce fuel use, a major aim is reduced engine speed.

First a technical point: the first term in Equation 2 is proportional to the number of engine revolutions in a trip. Let the vehicle be moving at speed v and in a gear with ratio g. We define v_{gear} so that if the vehicle were in top gear it would have to move at speed v_{gear} to have the same engine speed. There are two cases. In the first, the vehicle moves at constant speed v:

$$v_{gear} = (g/g_{top})v \tag{4a}$$

In the second, the vehicle moves at a variety of speeds. While in the gear with ratio g,

$$v_{gear} \approx (g/g_{top})v_{w.a.} \tag{4b}$$

where $v_{w.a.}$ is the average speed in that gear. Using the gear shift schedule of the FTP, a good approximation to v_{gear} in the form of Equation 4b is 24.6 m/sec (55 mph) for M5 (manual five-speed) transmissions.

Starting with the EPA urban driving cycle (UDC) as the base case, consider that, with aggressive driving, gears are shifted at 125 percent of the velocities designated in the FTP. In the latter, gears are shifted up or down at 6.7, 11.2, 17.9, and 22.3 m/sec (15, 25, 40, and 50 mph), with an M5 transmission. According to Equation 2 this results in a 10 percent increase in fuel use (modeled with AVPWR).

Correspondingly, a shift indicator light (installed as original equipment in some cars) encourages shifting at about 80 percent of the FTP shift-schedule velocities. According to Equation 2, this results in a 9 percent fuel savings in the UDC (modeled with AVPWR). This savings is typical of that observed in tests (*5*). This kind of gear shifting is not feasible during rapid acceleration.

The savings from following a shift indicator light in the EPA highway cycle are less. In top gear, v_{gear} is roughly 23 m/sec (51 mph), and the corresponding fuel savings in the model are 3 percent. This estimate is in rough agreement with test results, but the latter are highly variable (*5*).

Cruise Fuel Economy

In constant speed, or cruise, driving, $v_p = \bar{v} = \bar{v}_r \equiv v$, the α_{brake} term is zero, and $t_C = t_D = 0$. Thus Equation 2 becomes

$$\varepsilon_{cruise} = \alpha_{f.pwr} v_{gear}/v + \alpha_{tire} + \alpha_{air} v^2 + \alpha_{acc}/v \tag{5}$$

where Equation 4b is used for v_{gear}. (The use of Equation 4b smears the velocities with respect to gear shifting and so eliminates irregularities associated with the actual gear-shift velocities.) The fuel economies in cruise driving are shown in Figure 1 for the vehicle AVPWR (appendix). For today's streamlined cars, the maximum fuel economy at constant speed, v_{opt}, is near 23 m/sec (50 mph). The fuel economy falls off rapidly at low speeds. In particular, today's powerful engines are very inefficient at low power output. To illustrate this mismatch, the engine power required for the car AVPWR in cruise driving is also shown. The power requirement in urban cruise speeds is well under 10 kW, but the engine has power capability over 100 kW.

A more explicit view of the poor fuel economy at low speed is given in Figure 2. The source of inefficiency is the generalized engine friction, the $1/\bar{v}$ term, in Equation 2. This inefficiency is due to the large rate of fuel use at zero power output just to run a large engine.

Fuel Economy at High Speed

When the average speed is much higher than the optimal speed of about 22 m/sec (50 mph), the fuel economy decreases dramatically as the speed increases. This is what happens in driving on open highways, where the average speed has far surpassed 25 m/sec (55 mph). From Equation 5 we see that, since $v_{gear} = v$ (Equation 4a), the fuel consumption per mile is linear in v^2, except for the relatively small accessories term.

For AVPWR, the reductions in fuel economy from increasing the highway speed from 24.6 m/sec (55 mph) to 29.0, 33.5, and 44.7 m/sec (65, 75, and 100 mph) are 10, 20, and 40 percent, respectively.

Maximum Fuel Economy

What is the maximum fuel economy a given car can achieve? More specifically, in what kind of driving pattern does a car achieve maximum fuel economy? Consider a driving pattern with a lot of slow deceleration, with the brake seldom used. Call this pattern coastdown driving and the FE coastdown FE. An investigation of this issue (*6*, p. 117 ff) reveals that to achieve maximum fuel economy, you should first accelerate the car quickly, but not too quickly, to perhaps 33 m/sec (75

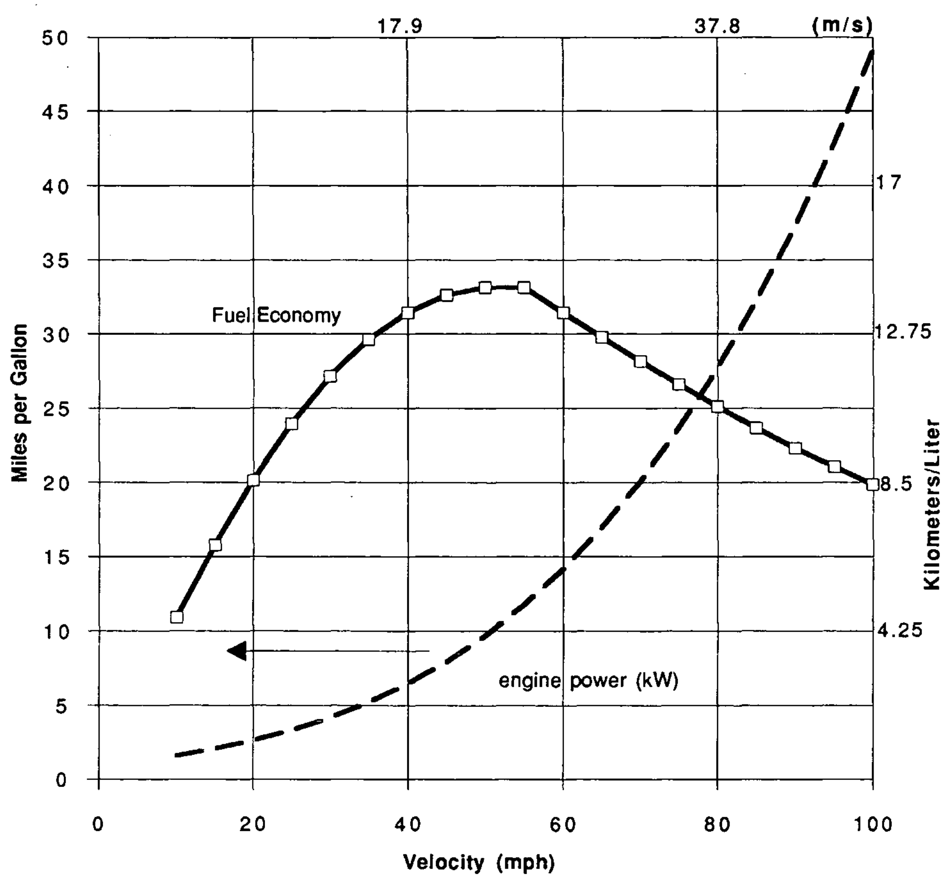

FIGURE 1 Fuel economy and power in cruise driving (car: AVPWR).

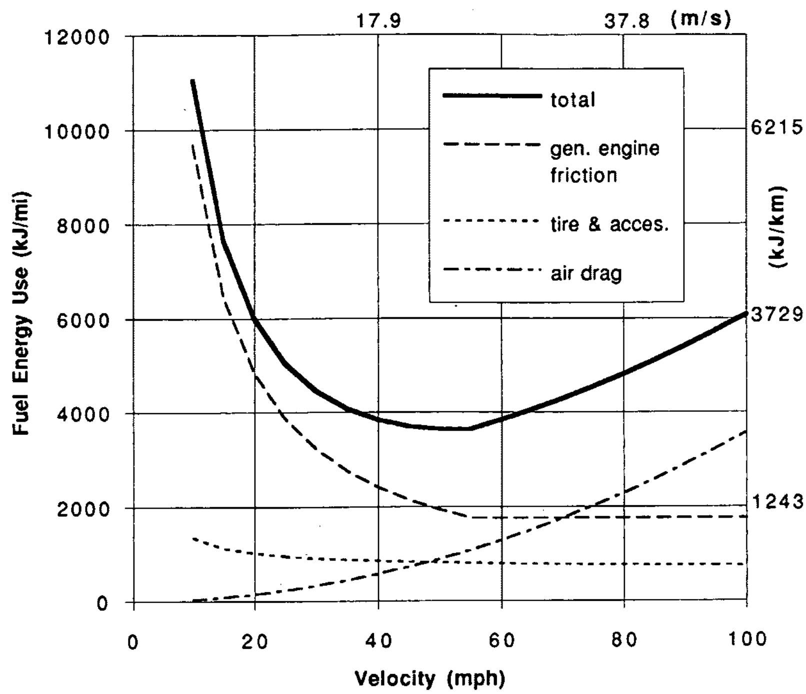

FIGURE 2 Specific fuel use in cruise driving (car: AVPWR).

mph), then let it coast to a stop. [The model does not account for rich operation of engines at high power (i.e., the use of high fuel-air ratios), which is a common design feature. This means that if one accelerates very rapidly or drives at very high speeds, the rate of fuel use is substantially higher, about 30 percent, than shown by Equation 2.] With repeated driving subcycles like this, you can improve the FE by 52 percent with average speed equal to that of the UDC, 8.8 m/sec (19.6 mph).

If you increase $\bar{v}$, the coastdown FE also increases until $\bar{v}$ reaches the cruise optimal speed v_{opt} (see Figure 3, fine-dashed line). For AVPWR, v_{opt} = 22 m/sec (49 mph), and the cruise optimal FE = 16.3 km/L (38.3 mpg).

Is coastdown driving with coastdown the most fuel-efficient driving? The answer is a surprising no. "Idle-off" driving with coastdown is more efficient. The definition of idle-off driving is that you turn off the engine and declutch when the vehicle coasts down. Thus $\alpha_{f,idle}$ = 0 (appendix). We get, for AVPWR,

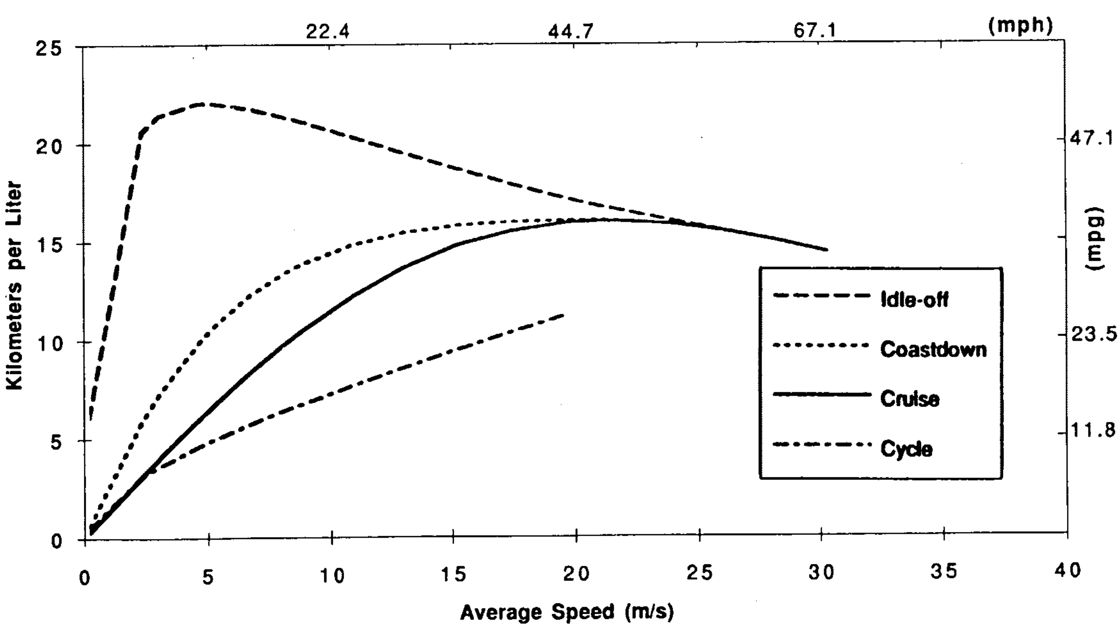

FIGURE 3 Maximum fuel economy.

with $\bar{v}$ = 8.8 m/sec (19.6 mph), about 2.4 times better fuel economy than the driving cycle FE. (Here we again limit the maximum speed to 75 mph.) Unlike the other FEs, the idle-off FE peaks at very low average velocity [around 4.5 m/sec (10 mph)]. The long-dashed line in Figure 3 shows how the idle-off FE changes with the average speed. Table 1 gives the comparisons among the various FEs for AVPWR at $\bar{v}$ = 8.8 m/sec (19.6 mph) except for cruise optimal driving, where v = 22 m/sec (49.0 mph).

In real driving conditions, the fuel economy can be dramatically improved by using the idle-off technique, even though the extreme coastdown driving discussed above is not involved. This has been discussed by several authors (*7–9*).

DRIVING-CYCLE MODEL

The model represented by Equation 2, although expressed in terms of macrocharacteristics of a trip, is still unwieldy for many purposes. In particular it involves five principal trip variables, two of which may be difficult to estimate (v_p and t_C) and are correlated with the others. By examining seven driving cycles, EPA urban and highway, Melbourne Peak, Beijing, ECE 15, Japan 10, and New York (*2*, Table 8), we find we can reduce the number of principal variables to three convenient trip characteristics.

It is often convenient to express fuel consumption as a function of overall average speed. L. Evans and others have shown how $\bar{v}$ alone enables a fairly good approximation of the effects of driving patterns on fuel economy (*10–14*). Our purpose here is to include the effects of other driving variables as well as to continue to express all the relationships in terms of fundamental engine and vehicle characteristics.

From study of the seven driving cycles we obtain the Driving-Cycle Model [adapted from Feng (*6*)]:

$$\varepsilon_{\text{fuel}} = \varepsilon_{\text{cruise}}(\bar{v}) - (\alpha_{\text{f.pwr}} v_{\text{gear}} - \alpha_{\text{f.idle}})(1 - \gamma^{-1} + t_C)/\bar{v} + \alpha_{\text{air}}\bar{v}^2(\lambda\gamma^2 - 1) + \alpha_{\text{brake}}\beta\gamma\bar{v}v_{\text{ff}}n \quad (6)$$

where $\gamma \equiv 1/(1 - t_D)$, and we suggest the following approximations:

$$t_C \approx (1.4\lambda - 1)s \quad (7)$$

$$n \approx \frac{1}{2\tau_{\text{stop}}} s/\bar{v} \quad (8)$$

where

$$s \equiv (1 - \sqrt{\gamma\bar{v}/v_{\text{ff}}})/\gamma \quad (9)$$

Here the principal trip-dependent variables are

$\bar{v}$ = overall average speed (or one can use $v_r \equiv \gamma\bar{v}$)
v_{ff} = free-flow velocity (discussed below), and
γ = vehicle stop factor (or one can use $t_D \equiv 1 - \gamma^{-1}$).

Although the principal variables are essentially independent, there is a bound imposed by v_{ff}:

$$v_r = \gamma\bar{v} \le v_{\text{ff}} \quad (10)$$

Subsidiary variables that can be adequately estimated a priori are v_{gear}, λ, and β, as before, and τ_{stop}, the average braking time per stop, 6.7 sec in the EPA urban cycle and about 5 sec in the other urban cycles. τ_{stop} is about 1 min in the EPA highway cycle.

The Driving-Cycle Model, Equation 6, with the approximations given in Equations 7 and 8, is less accurate than Equation 2. The advantages are the smaller number of principal variables, their greater independence, and their easy interpretation. The new variable v_{ff} is defined in the driving cycles as follows:

$$v_{\text{ff}} = v_p^2/v_r$$

However, we find it can be estimated roughly as the speed limit plus 6.7 m/sec (15 mph) on freeways and speed limit plus 2.2 m/sec (5 mph) on urban roads. The column v_{limit} in Table 2 is the authors' estimate. The beauty of the variable v_{ff} in this form is that it is independent of $\bar{v}$ in that it depends on road and speed limit characteristics and not on any particular trip.

The variables $\bar{v}$ and v_{ff} are powerful predictors of fuel use in the context of the seven driving cycles. Is more detail needed for the kinds of applications to be made? To consider the important class of travel in which the fraction of vehicle stop time, t_D, is high, more detailed description of the travel, as provided by t_D, or γ, and perhaps n, may be needed.

Determination of Modified Driving Cycles

Driving patterns have changed since the specification of the regulatory driving cycles now in use. In the early 1980s, the discrepancy in FE between the FTP and actual driving was estimated to be 15 percent (*15*). It has been roughly estimated that this will rise to 30 percent by 2010 (*16*), and we estimate that it has already increased to between 20 and 25 percent. Some of the difference between test and actual conditions is associated with inaccuracies in testing (like tire slip on the dynamometer) and the poorer conditions, or maintenance, of actual vehicles in use than the new vehicles being tested. The

TABLE 1 Maximum Fuel Economy for AVPWR

	Cycle	Cruise	Coastdown	Cruise (opt)	Idle-off
$\bar{v}$ m/s (mph)	8.8 (19.6)	8.8 (19.6)	8.8 (19.6)	21.9 (49.0)	8.8 (19.6)
v_p m/s (mph)	13.8 (30.9)	8.8 (19.6)	33.5 (75.0)	21.9 (49.0)	33.5 (75.0)
FE km/ℓ(mpg)	9.1 (21.4)	10.2 (24.1)	13.8 (32.5)	16.3 (38.3)	21.5 (50.7)

TABLE 2 v_{ff} **in Seven Driving Cycles (m/sec, mph)**

Driving Cycle	v_{ff}	v_{limit}
EPA Highway	32.8, 73.5	24.6, 55*
EPA Urban	17.7, 39.6	15.6, 35
Melbourne	17.9, 40.1	15.6, 35
Beijing	11.2, 25.0	11.2, 25
Europe	12.4, 27.8	11.2, 25
Japan	12.0, 26.8	11.2, 25
New York City	14.7, 33.0	13.4, 30

* The EPA Highway Cycle involves a mix of four rural road types: principal arterial, minor arterial, collector, and local.

main reasons for the increase in the discrepancy are, presumably, increased congestion, increased open highway speeds, and perhaps, more urban-type driving. Both to reduce the differences between test and actual driving and to identify the sources of change, EPA is carrying out a program of observation on typical driving.

The model, Equation 2, suggests that cycle modifications be created on the basis of measurement of a few macrocharacteristics of driving instead of repeating the data-intensive process associated with the definition of the present cycles, which are second-by-second velocity patterns. Equation 2 depends on five principal summary variables for a trip. Equation 6 reorganizes some of these variables and suggests that three or four may be enough to define a trip for purposes of fuel consumption. Average speed, free-flow velocity, fraction of time vehicle stopped and, perhaps, stops per mile should be measured, and fuel-use weighted averages created. Another variable is implicit in the engine friction characteristic and needs to be incorporated in specification of a driving cycle for fuel economy: cold start. Whereas a revised cold start characterization may be needed, we have not studied what it should be.

In addition, certain driving characteristics are critical to emissions but not important for fuel use. Outstanding among those in an acceleration characteristic, for example, the distribution of the variable velocity times acceleration. Engine power output is closely related to the latter, and emissions are very sensitive to power output. Careful study is needed to define cycles for regulation of emissions; we do not suggest that our work relating to driving cycles for fuel economy implies the contrary.

We illustrate the effects on fuel economy of changing the three principal variables one at a time. [v_{gear} = 24.6 m/sec (55 mph) (given by Equation 4b) is used in all the remaining calculations.] Fuel economy is most sensitive to overall average speed, $\bar{v}$ (see Figure 4). For example, vary $\bar{v}$ 10 percent up (or down) from its UDC value of 8.8 m/sec (19.6 mph) while fixing v_{ff} at its UDC value and the fuel economy is increased (or decreased) 5 percent. At the relatively low speeds of the urban cycle, the dominant cause of fuel use is generalized engine friction, which is proportional to the number of engine revolutions in the trip. If the running speed is increased while engine speeds remain about the same, the trip time decreases and the total number of engine revolutions is decreased.

Fuel economy is also sensitive to free-flow velocity, v_{ff} (Figure 5). Decreasing v_{ff} by 25 percent from its UDC value of 17.7 m/sec (39.6 mph) while fixing $\bar{v}$ at its UDC value increases

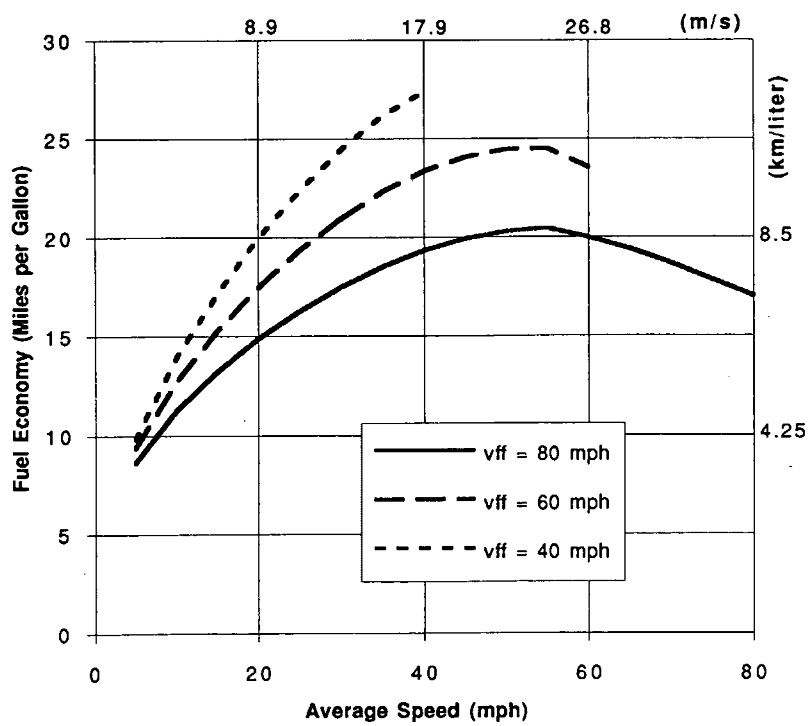

FIGURE 4 Fuel economy and average speed (stop time = 0.00; car: AVPWR).

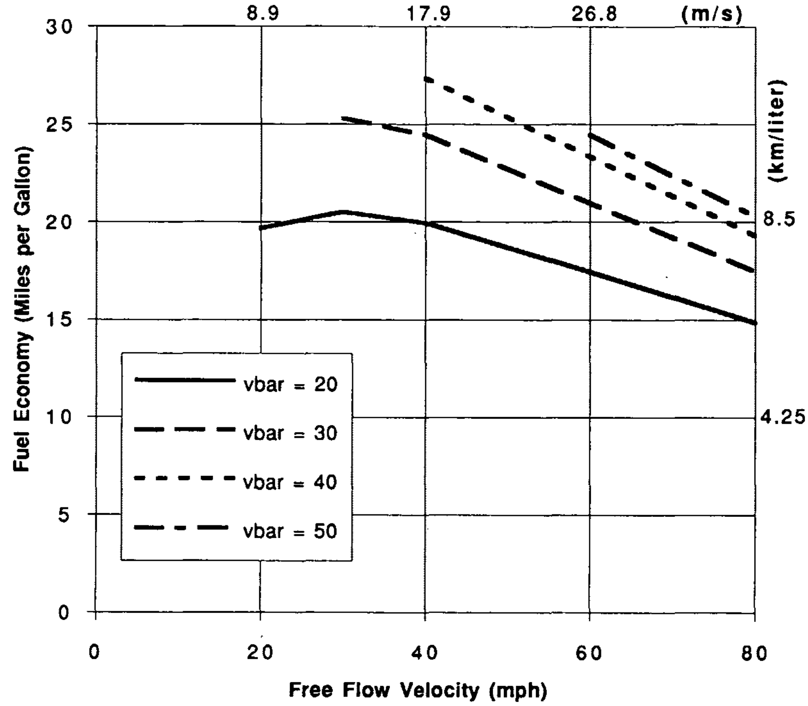

FIGURE 5 Fuel economy and free-flow velocity (stop time = 0.0; car: AVPWR).

the fuel economy by 5 percent. Fuel economy is less sensitive to vehicle stop time, although it improves slightly with increased stop time under most conditions (Figure 6).

Effect of Traffic Smoothness on Fuel Economy

From Equation 6, we see that fuel economy is determined by three factors: average speed $\bar{v}$, free-flow speed v_{ff}, and vehicle stop time. In this section, we will use Equation 6 to answer the question, How does traffic smoothness affect fuel economy?

There are two issues. The first is, If the average speed of total trip time is fixed, how can the traffic pattern be changed to improve fuel economy? From Equation 6, the answer is by reducing the free-flow speed v_{ff} and perhaps by increasing total vehicle stop time.

Assuming crowded roads such that the average travel speed cannot be increased, the answer is to reduce v_{ff}. While the primary determinant of fuel economy is average speed, Equation 6 shows that a road characteristic, the free-flow speed, is also important. In Figure 5 one finds, for example, that if $\bar{v}$ is fixed at 13.4 m/sec (30 mph), when v_{ff} is reduced from 26.8 to 17.9 m/sec (60 to 40 mph) the fuel economy of AVPWR increases 16 percent. The dependence of the fuel economy on roadway types has been discussed previously by Levinsohn and McQueen (*17,18*). They say, "In free flowing traffic conditions, the road type does not have an effect upon fuel consumption at a given speed; however, if there is congestion, vehicle fuel consumption will vary with road type." Their studies show that the speed that is important when related to traffic volume is the attempted speed of the automobile.

If the $v_{ff}/\bar{v}$ ratio is high, there is a lot of rapid acceleration and deceleration, with increased braking and air drag. The maximum attempted speed can be reduced by reducing the speed limit at times when traffic congestion is heavy, as long as overall average speed is not reduced, and by using traffic light control techniques, such as signal green wave, ramp control, and so on (*19*).

The second answer, to increase vehicle stop time t_D, is obscure at first glance. When you increase t_D but keep $\bar{v}$ and v_{ff} unchanged, you are decreasing the amount of low-speed driving with its high fuel use associated with generalized engine friction (Figure 2). The overall balance of effects is such that there is a small benefit from increased vehicle stop time (Figure 6). This means that, in principle, metering of traffic flow, as in the westbound approach to the San Francisco Bay bridge, is in itself helpful.

The above two measures not only increase the vehicle fuel economy but also can increase road capacities (*20*). Smoother traffic can reduce spacing or headway between cars, thus increasing capacity.

The second issue is, Can the average speed be increased? Among other benefits, fuel economy will usually improve. We discuss only this latter point: the main issue is whether v_{ff} is increased as part of the strategy to increase $\bar{v}$. If so, the increase in fuel economy is less. In Figure 5 we see that if one increases $\bar{v}$, the fuel economy is increased the most if v_{ff} can be kept fixed or, even better, decreased. Meanwhile if v_{ff} is greatly increased as part of the strategy to increase $\bar{v}$, the fuel economy may not be improved.

Traffic Management Analysis

The Driving Cycle Model is converted into numerical form using the definitions of vehicle factors α in the appendix and

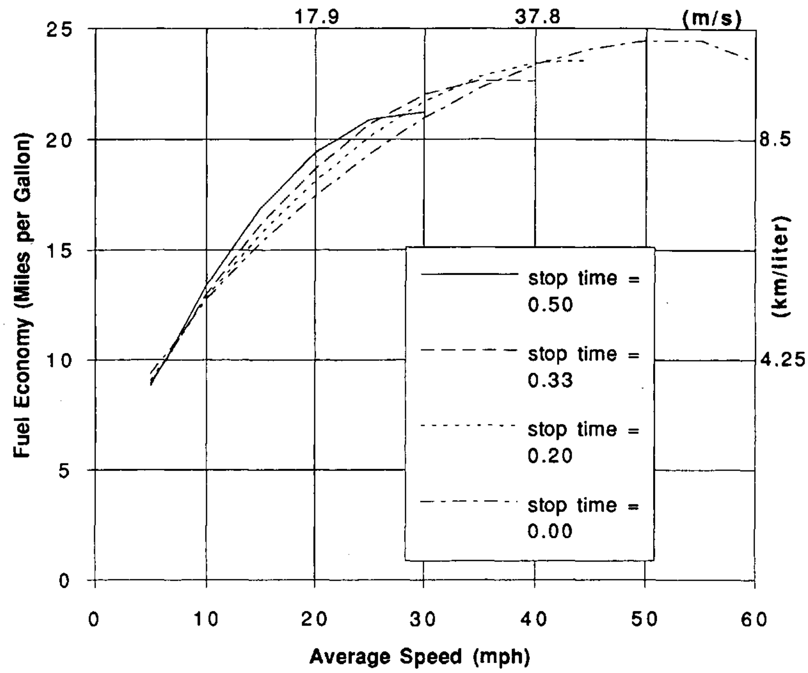

FIGURE 6 Fuel economy, fixed free-flow velocity, and various relative stop times (free-flow velocity 60 mph; car: AVPWR).

expressing all the dependence on vehicles in terms of two characteristics: inertial weight, W, and the product of engine displacement and (N/v), where N/v is rpm/mph in top gear. This procedure is analogous to that used to obtain Equations 32 and 33 of An and Ross (*2*). For convenience, the vehicle characteristics are related to the AVPWR base case:

$$M_0 = 1588 \text{ kg} \qquad (W_0 = 3500 \text{ lb})$$

and

$$V_0(N/v)_0 = 3.1\text{L} \times 1.306 \frac{\text{rps}}{\text{m/sec}} \left(3.1\text{L} \times 35 \frac{\text{rpm}}{\text{mph}}\right)$$

As suggested by Equations 6, 7, and 8, only three driving characteristics will be represented: $\bar{v}$, v_{ff}, and γ. We also express these variables in terms of ratios to a base case, the EPA urban driving cycle: $\bar{v}_0 = 8.8$ m/sec (19.6 mph), $v_{ffo} = 17.7$ m/sec (39.6 mph), and $\gamma_0 = 1/0.81$. We find the following for urban driving (in kJ/mi):

$$\varepsilon_{\text{fuel}} = \frac{[5{,}263 - 3{,}106(t_C + t_D)]}{(\bar{v}/\bar{v}_0)} \frac{V(N/v)}{V_0(N/v)_0} + \left[682 + \left(239\frac{W_0}{W} + 159\right)\frac{\gamma^2\bar{v}^2}{\gamma_0^2\bar{v}_0^2} + 925\frac{\gamma v_{ff} s}{\gamma_0 v_{ffo} s_0}\right]\frac{W}{W_0} \tag{11}$$

where

$$t_C + t_D = 1 - 0.81\gamma/\gamma_0 + 0.30\, s/s_0 \text{ and}$$

$$s = 0.81\left(1 - 0.7817\sqrt{\frac{\gamma\bar{v}}{\gamma_0\bar{v}_0}\frac{v_{ffo}}{v_{ff}}}\right)\frac{\gamma_0}{\gamma}.$$

The first term in Equation 11 incorporates the generalized engine friction and the small vehicle-accessories term. The second term incorporates the tire, air drag, and braking terms, in that order. The coefficients are derived from measured physical quantities in essentially all cases; they are not regression coefficients. To convert Equation 11 to grams of fuel per mile, if needed, one multiplies every term on the right-hand side by the factor 0.227 (g/kJ).

Equation 11 is in a form to be used to calculate fuel use as an adjunct to traffic flow analysis. One first needs to decide what parameters characterize the vehicles in question. (The numbers in Equation 11 apply to M5 cars of recent vintage.) Then one can apply the equation to vehicle miles of travel on segments of roadway where specific values of average speed and free-flow speed apply, keeping in mind that average speed and free-flow speed are the critical parameters; accuracy in other parameters is less important.

CONCLUSIONS

The relatively simple equations presented in this paper enable accurate determination of fuel consumption in a trip in terms of basic characteristics of the vehicle and trip. The principal variables are easily interpreted physical quantities rather than regression coefficients, and the equation is the final result, not an input to a computer simulation program. These models combine trip and vehicle characteristics and can readily be expressed to yield fuel use for any mix of vehicles for which a few fundamental attributes can be estimated. We have suggested several applications; we believe there are many others.

TABLE A-1 Characteristics of AVPWR

V	engine displacement	3.1 liters (189 CID)
W	inertial weight	1588 kg mass (3500 lbs.)
N/v	engine/vehicle speed ratio (in top gear)	1.036 rps/(m/s) (35 rpm/mph)
$C_D A$	air drag factor	0.68 m^2

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APPENDIX VEHICLE PARAMETERS

The vehicle-dependent coefficients in Equation 2 are as follows:

1. Generalized engine friction in powered operation:

$$\alpha_{f.pwr} = kV(N/v) = 60kV(N/v) \quad \text{(kJ/mi)} \tag{A-1}$$

where

V = engine displacement (L),
(N/v) = (engine speed/vehicle speed) in top gear (rpm/mph),
k = V/a, and
a = the engine friction characteristic.

For current vehicles, we use the estimates $k = 0.27$ kJ/lit. rev. for the EPA urban driving cycle, where the engine starts cold, and $k = 0.25$ kJ/lit. rev. when it is hot (*1,2*).

2. Generalized engine friction in idle operation:

$$\alpha_{f.idle} = kVN_{idle} = 60kVN_{idle} \quad \text{(kJ/hr)} \tag{A-2}$$

where N_{idle} is idle engine speed in rpm and k can be taken from Equation A-1. A convenient approximation that we use is $N_{idle} = 900(1 - V/14.8)$ rpm. For Equation 11 we use $N_{idle} \approx 21\ (N/v)$.

3. Tire rolling resistance:

$$\alpha_{tire} = C_R W/\eta\varepsilon = 4.45 \times 1.609 C_R W/\eta\varepsilon \quad \text{(kJ/mi)} \tag{A-3}$$

where

C_R = coefficient of rolling resistance (dimensionless, which we take to be 0.010),
W = inertial (loaded) vehicle weight (lb), and
ε = efficiency of the transmission system (taken to be 0.90, dimensionless).

η is defined by Equation 1 and is taken to be 2.45 (dimensionless). The numerical factors are the ratio of Newtons to lb and km to miles, respectively.

4. Air resistance:

$$\alpha_{air} = \rho C_D A/2\varepsilon\eta$$
$$= 0.5 \times 1.20(0.447)^2\ 1.609 C_D A/\varepsilon\eta$$
$$\text{(kJ/mi)(mph)}^{-2} \tag{A-4}$$

where

ρ = 1.20 kg/m^3 is the density of air,
C_D = coefficient of drag of the vehicle (typically about 0.35 for 1992 cars), and
A = frontal area of the vehicle in (m^2) (about 2.0 for an average car). The factor 0.447^2 is to convert the v_r^2 in Equation 2, which is in mph, to m/sec.

5. Brakes:

$$\alpha_{brake} = M^*/2\varepsilon\eta$$
$$= \frac{1.035 \times 0.454 \times 0.447^2}{2{,}000}\frac{W}{\varepsilon\eta} \quad \text{(kJ)(mph)}^{-2} \tag{A-5}$$

where M^* is the vehicle mass including the effects of rotational inertia (a factor of 1.035). The factor 0.454 converts pounds to kilograms. The v_p and n factors in Equation 2 should then be in mph and mi^{-1}, respectively, to obtain kJ/mi.

6. Vehicle accessories:

$$\alpha_{acc} = P_{acc}/\eta = 3{,}600\ P_{acc}/\eta \quad \text{kJ/hr} \tag{A-6}$$

where the power to operate the vehicle accessories, such as air conditioning, power brakes and steering, lights, and audio system is in kW (which we take to total 0.75).

In this paper we consider an average new U.S. car, denoted AVPWR, to have the characteristics given in Table A-1.

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